COMPUTER AIDED MANUFACTURING OF SPIRAL BEVEL GEARS

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ABSTRACT : The spiral bevel gear has the best qualification when comparing with the others of gears. However, Spiral bevel Gear up to now was still manufactured by specific machines where the combination of envelop motions to create the tooth surface of Spiral bevel gear is usually complicated. Therefore, the gear surface quality is usually not accurate, not stabilized and high cost.

This study aims to apply of CAD technologies into the metal cutting field. Especially, the tendency of using CNC (Computer Numerical Controller) machine on manufacturing Spiral bevel Gear is the best solution which can satisfy most of the required specifications of spiral bevel gears. Otherwise, the most significance is to increase the quality of spiral bevel gears and to simplify enormously the machine toll for making them.

In order to be able to machine spiral bevel gears on CNC machine, a five axis CNC machine with 5D contouring control is required. A CAD/CAM system with 5 axis tool path generation capabilities is necessary and a standard postprocessor is also required.

The most significant problem of using CAD technology and CNC machine to made Spiral bevel is that we can use the output file from the Postprocessing of CNC machine in checking model, diagnosing errors, simulating and measuring the surface quality of a pair meshing Spiral bevel gear.

II - INTRODUCTION

Spiral bevel gear is a perfect example of a part which can be very efficiently designed with the help of a computer. The application of CAM technology and CNC machine in making spiral bevel gears is quite preferable. Because it is satisfied almost all of the specified targets of spiral bevel gears such as:

- To get the required accuracy of gear tooth surface and the surface hardness.
- Not has interference phenomena or undercutting.
- The contact zone is regular for a pair of tooth when meshing.
- Have smoother tooth engagement, quietness of operation
- The high loaded capability, high life time.
- Can work at higher permissible speeds
- Occupy small space in machine.

The main objective of this study is aimed to analyze and gain expertise on how the CAD technology to be used on making the 3D geometrical model and technological advantages of 5 axis CNC machining. This task is fulfilled by machining successful a spiral bevel gear on CNC MAHO600e machine by using Unigraphics II CAM software at AIT (Asian Institute of Technology). The study achieves the following objectives:

1.Developing a new five-axis machining algorithm which satisfies the specifications of spiral bevel gears on MAHO600e CNC machine.

2.To study the application of CAM technology in process planning, and machining spiral bevel gears.

3.To suggest the best methodology in getting toolpath, manufacturing and controlling quality of spiral bevel gears in the metal cutting sector.

We will develop a typical model for spiral bevel gears of "Klingelnberg" cutting method by making one spiral bevel gear on CNC machine that based on the available CAD/CAM system at CIM lab in AIT.

However, it is impossible to get the required gear tooth surface accuracy which exceeds more than the machine tool accuracy (0.001 mm for MAHO 600E CNC machine). Manufacturing should be able to generate the tool path automatically providing tool tip coordinates and orientation of the tool which will ultimately produce the required shape with the required accuracy. Because of hardware and software limitations, so the extremely high accuracy of spiral bevel gear can not be maintained.

Machining mode of the spiral bevel gears have to be done on five-axis CNC milling machine. In the process planning phase, certainly that we can meet some trouble problems while making tool path. Therefore, a modification of CAD geometric model for conveniently making tool path and preventing undercut phenomena in this phase should be done.

III - PROCESS PLANNING

The process planning was described in detail at Figure 3.1

In our study the process is organized in hierarchical rules (Fig 3.2) . The antecedents of higher level classes are inherited by the lower level classes. The major advantages of this approach are that it is easy to understand and checking for later phases, easy to compensate tolerance and to correct later.

3.1 "Equipment " Selection

3.1.1 Machine tool selection

To select the machine tool we need to compare at least the following characteristics like geometry of part , precision, machine type, processing type, work table size, work envelop, spindle horsepower, spindle taper type, feed rate and speed range, axis torque, accuracy, available in tool library, tool magazine, preselect tool equipment, range of axis movement, speed of transferring data, cost, etc. These capabilities should be matched with the required specifications In this study the 5 axes milling machine was chosen to machine spiral bevel gears instead of 3 axes milling machine because 3 axes milling machine have some limitations about tool motion and envelop motion when compare with 5 axes machine.

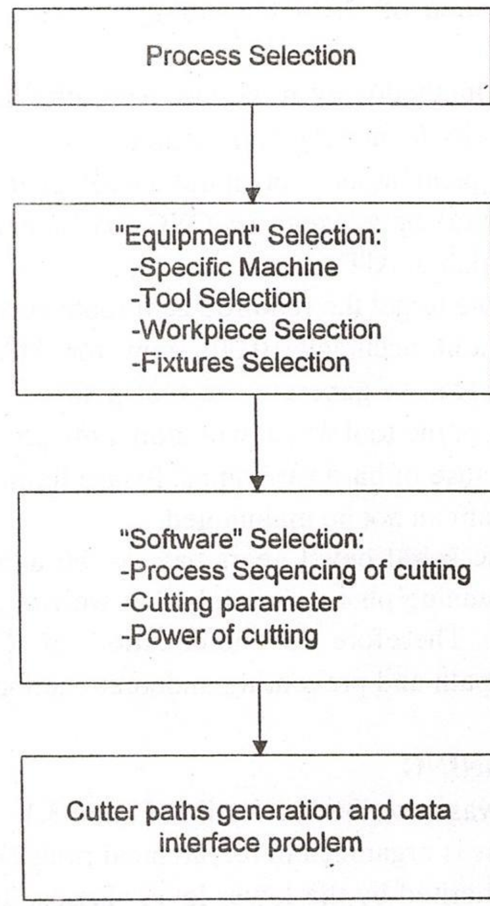

Figure. 3.1 General Procedure of Process Planning

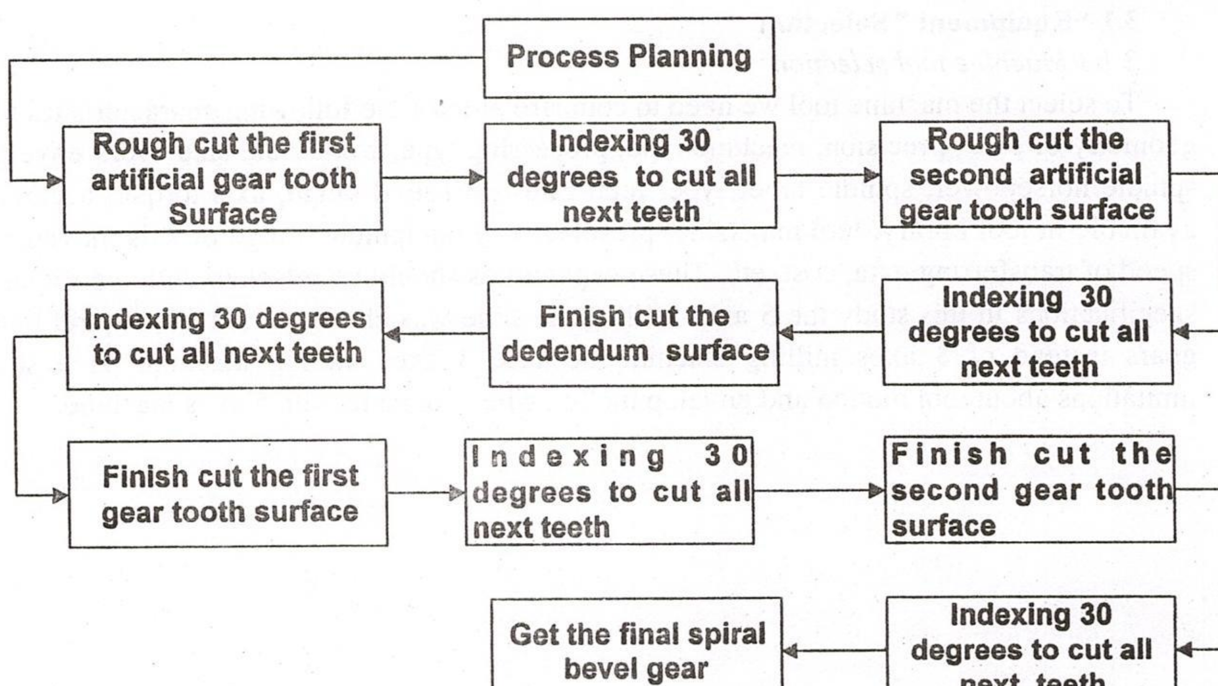

Figure. 3.2 Diagram of process selection

3.1.2 Machining technique considerations

To understand well the machining technique, we need consider some milling operations available in Unigraphics software. We will apply five axes milling mode and swarf milling technique for machining the surfaces of spiral bevel gear.

With five axis milling mode allows the usage of flat end mill or peripheral mill for machining of those surfaces. So processing time will be reduced very much. Depending on the way of surface is machined we have three basic methods

- Head milling with Flat end Mill.
- Peripheral Milling.
- Milling with bottom of cutter

3.1.3 Tool selection

There are 3 kinds of tool to use for milling, namely flat end mill, ballnose mill and bullnose mill. The exact choice would depend on the kind of milling operation to be done and the surface finish required. There are several decisions to be made in tool selection, variables on a tool include:

•Tool material: HSS (high speed steel) , cemented Carbide , Carbon tool steel, medium alloy steel, cast alloy tool, Oxid tool materials (Caremics) , etc.

•Tool geometry: flat-end mill, ballnose, bullnose

•Tool parameters: Rake angle , location of cutting edges (principal and auxiliary cutting edges), nosed radius, Body of tooth, Gullet, helix angle , number of flutes, etc.

•Tool type (milling tool).

•Tool dimension: overall length, flute length, diameter.

The selection of tool type is determined by the process type and is probably the easiest to decide. The rest of decision has to be made based on the workpiece material, hardness, feature dimension, and feature approach clearance. Rules for tool selection should include a rule for clearance checking. In order to optimize the process plan, it is desirable to minimize the number of tool used. For milling a rule should be written to use the same tool for several features as long as the difference among optimal tool sizes for these features are small. Since above principles with an inventory of the available tool in CIM-lab, the tool are chosen for our application in the Table 3.1 below

3.1.4 Workpiece selection

The kind of material is used for machining in our study is an impregnated-resin wood block available at the CIM lab. The blank-part is turning by lath machine in order to create correctly the dimension outside of spiral bevel gear, also it is conveniently used as the referenced surfaces for the set up process when we machine teeth. The spiral bevel gear is cutting here is the pinion which has module $m_n = 12mm$, number of teeth is Z = 12, gear width b = 100mm, the big diameter at the addendum cone surface of workpiece is 168.37mm.

Table 3.1 Tool selection

Toll No.	Description	Diameter (mm)	corner radius (mm)	Number of flutes	flute length (mm)	Total length (mm)	Operation
1	Flat end mill Φ6	6	0	2	30	70	rough cut the slot gear and finish cut of gear tooth the surfaces
2	Flat-end mill Φ4	4	0	2	35	75	finish cut of the dedendum surface

3.2 "Software" Selection

3.2.1 Operation sequencing

In practice, the selection often is based on the conventional cutting methods or inherited experience. We tried to find a good solution which satisfies all constraints, the best solution can be found in our case is illustrating in Figure 3.3 below

We look that in the diagram above, if we machine whole of gear which has number of teeth is Z, then after machining one tooth at one operation we do indexing the workpiece or rotate tooth path by one angle: $\varphi_{rotate} = \dfrac{360}{Z}$ = 30 degrees in order to machine all remaining teeth Z before continuing to machine the next milling operations.

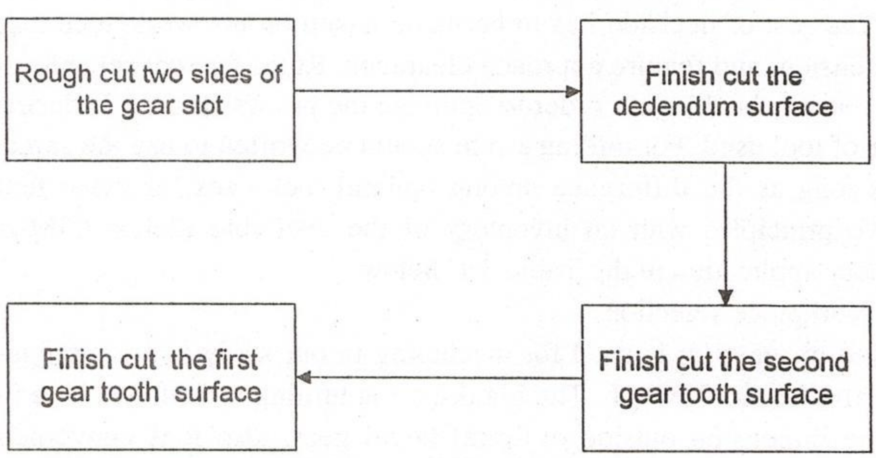

Figure. 3.3 Optimum sequence milling

3.2.2 Selection of cutting parameters

3.2.2a Select Feed rate and Spindle speed

With the spiral bevel gear, we reference to the metal cutting handbook of Russia and the cutting parameters can be obtained as follows:

- Material of workpiece: Cr.Ni Steel. - Cutting Velocity: $v = 30m/\min ute$

- Maximum of depth of cut: b = 5mm - Tool Material: HSS P18, hardness = 62÷65HRC

3.2.2b Cutting Power Selection

In our case, because the cutting power in rough cut is greater than finish cut. We will calculate the cutting power for the case of face milling process in order to select motor.

$$N = \frac{1000v}{\pi d} = \frac{1000 \times 30}{\pi \times 6} = 1193 RPM$$

$$\omega = \frac{2\pi N}{60} = \frac{2\pi \times 1193}{60} = 124.9 rad/\sec \Rightarrow P = M\omega = 5265.75 \times 124.9 \approx 5.8kW$$

If we include the efficiency $\eta = 0.98$ then $P_{Motor} = \frac{P}{\eta} = \frac{5.8}{0.98} \approx 6kW$

We see that the power of our CNC machine MAHO600E has the spindle power equal to $P = 10kW > P_{calculate} = 6kW$, so The power of MAHO600E satisfies the power requirement for cutting.

Table 3.2 Feed rate and spindle speed selections

Tool No.	Description	Diameter d (mm)	Corner radius (mm)	Feed rate S (mm/m)	Spindle Speed (rpm)
1	Flat end-mill φ6	6	0	3,150	1,600
2	Flat end-mill φ4	4	0	2,100	1,800

In practice, the values of cutting parameters should be rounded to the nominal values of the machine. In our case, we can take the same value of spindle speed is 1,500rpm and feed rate is 800 mm/min for the machining process of spiral bevel gear.

3.2.2c Tolerance selection

The cause of tolerance capability is more complex. Many factors affect to the accuracy of the process which are included: tool wear, tool deflection, error of three jaws chuck, thermal deformation of machine too elements, tool and workpiece, control inaccuracy round out of tool assembly, fixture error, etc. The tolerance capability is caused by combination of these factors. It is not possible to predict the tolerance precisely. Therefore, the only feasible way is to rely on the experience base.

3.3 Process plan Description

Because spiral bevel gear is the symmetric part with the number of teeth is equal to 12, so we need only to create one tool-path for machining gear slot, after that we can rotate workpiece or rotate tool path by angle $\frac{360}{Z} = 30$ degrees about gear axis in order to cut all next remained teeth.

In our study, when machining the spiral bevel gear that has the surfaces not only in conical surface type but also in twist surface type so the process planning not simple as normal workpiece. We have to create two artificial surfaces on the gear slot with the purpose for conveniently making tool path in rough cut step.

On these artificial surfaces, they contain many of ISO parametric lines for easy to make tool path. These artificial surfaces should be created at the geometric modelling phase.

In our model the best operations can be applied is Parameter line Milling operation for rough cut two sides of the gear slot and finish cut the two gear tooth surfaces. Zigzag milling operation for finish cut the dedendum surface and the tool axis must be in kind of Swarf milling.

3.3.1 Rough cutting the gear slot in 5 axes mode by Parameter-line Operation

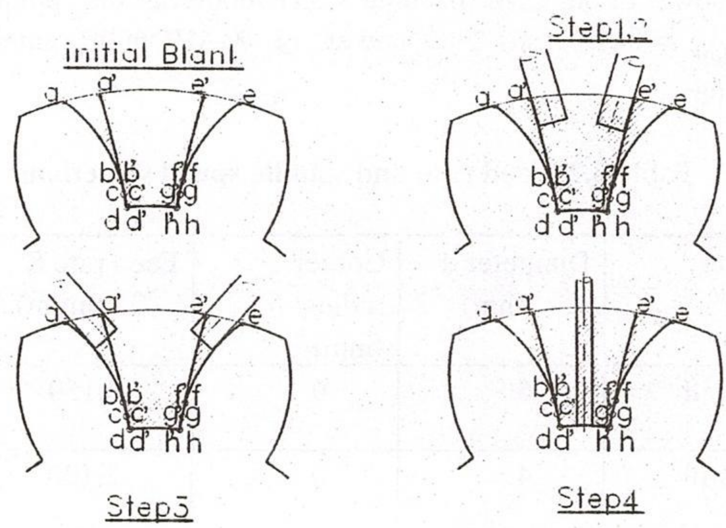

Figure 3.4 Some artificial surfaces to aid for the process planning

In this operation, we will machine the part of material $a'b'c'd'h'g'f'e'$ region in Figure. 3.4

3.3.2 Finish cutting

1/- Finish cutting of the first gear tooth flank surface in 5 axes mode by Swarf milling Operation. The part of material being taken out is $abcdd'c'b'a'$ region in Figure. 3.4

2/- Finish cutting of the second gear tooth flank surface in 5 axes mode by Swarf milling Operation. The part of material being taken out is $efghh'g'f'e'$ region in Figure. 3.4

3/- Finish cutting of the dedendum surface in 5 Axes mode by Zigzag surface Milling Operation. The part of material being taken out is the remaining stock of dh surface in Figure. 3.4

3.4 Tool path generating using Unigraphics II CAD/CAM system

3.4.1 Procedure

The final target of whole process is creating CNC program output for the motion control of CNC machine. The output of process planning is the CLSF file, this file is also the input file for Preprocessor of Unigraphics for creating next CL file. Finally, the Postprocessor of five axis machine will convert these CL files to CNC files in which the machine can understand to control the motion for machining spiral bevel gear. The whole process can be shown in Figure. 3.5 below.

3.4.2 Unigraphics machining output

The output of Unigraphics II CAM software is the cutter location source files (CLSF files). The CLSF file contains the coordinates of where (in Machine Coordinate System values) the cutting tool center line will travel to machine the workpiece. In which, it is consists of tool motion commands, control commands, feed rate commands. In addition, macro commands may be written into the CLSF file or retrieved from library.

3.4.3 CL data file

The CNC only "understand" the tool path of process planning if and only if the CAM vendors should be supplied the common format of cutter location data in CL file. The CL file can be get by output of UGII or by directly from GRIP/NC programming. The CL file is consists of a series of sets of X,Y,Z coordinate values for the tip of the cutter in sequence as it move around the geometry. There are three kinds of CL files that follow standard ISO3592 and ISO4393, they are namely:

BCL (Binary CL files): follow the ISO3592 standard, e.g. 0I0II0III000...

ACL-ASCII CL files: follow the ISO3592 standard, e.g. 5,5000,5,...

SCL-source CL files: follow ISO4343 standard like APT Syntax, e.g. GOTO/x,y,z,i,j,k

The major disadvantage of BCL files is its dependence on the computer platform, therefore and ACL or SCL format is suitable. The output of POST (Machine Post Processing) module of UGII follows type of SCL file.

3.5.4 Postprocessing

The postprocessor is the kind of software to convert the CL file into the CNC file which is used for controlling the machine in order to make the part. They are depend on the kind of CNC machine. In our case, the KUL post processor software is used for 5-axis MAHO600E machine. The output CL file of CAM module or GRIP/NC is the input for the postprocessor. The input of KUL postprocessor strictly follows the ISO3592 CL file standard. The KUL postprocessor requires the coordinates of the origin of the part coordinate system in machine coordinate along with the coordinates of the origin of the primary (B-axis) and the secondary axis (A-axis) in machine coordinates which are shown in Table 3.3 below.

Table 3.3 Primary and secondary Axis origins in Machine Coordinate System.

Axis type	X coordinates	Y coordinates	Z coordinates
Primary axis (B-axis)	298.854	0.0000	78.057
Secondary axis (A-axis)	298.925	177.278	0.0000

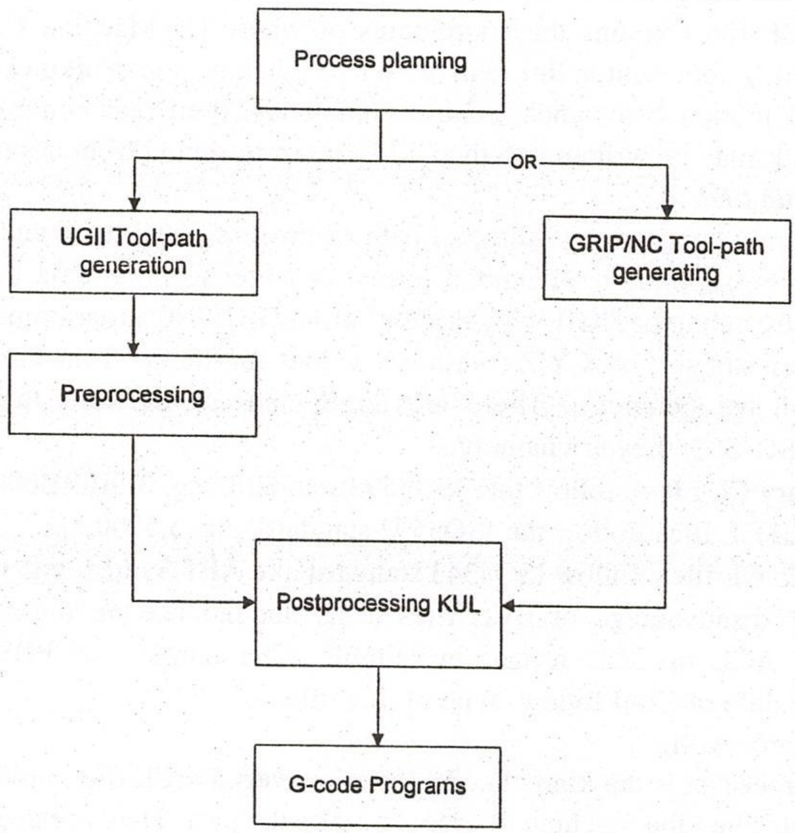

Figure. 3.5 Procedure for tool path generating

Below is the example of CNC file of the first artificial surface:

```
%PM
N91234(spiral1a.dnc)
N30(spiral1a.dnc)
N31G17 (xy-plane)
N32G51 (no reset axis)
N33S100M3
N34M5
N35G71(METRIC)
N36(orig x-298.920 y-177.278 z-120.991)
N37G93X0Y0Z0A60B0
```

N38T11M6(Undefined diam 6 cornRad 0)
N39G0X257.613Y182.34Z151.67A31.884B90S1500M3
N40G1Z148.67F800
N41X261.031Y182.327Z149.236A30.056B89.894F684
....
....ect,
N1063X257.102Y182.624Z122.955A31.884B90F750
N1064M5
N1065T0M6
N1066M30

The results of toolpath were shown from Figure 3.6a to Figure 3.6d

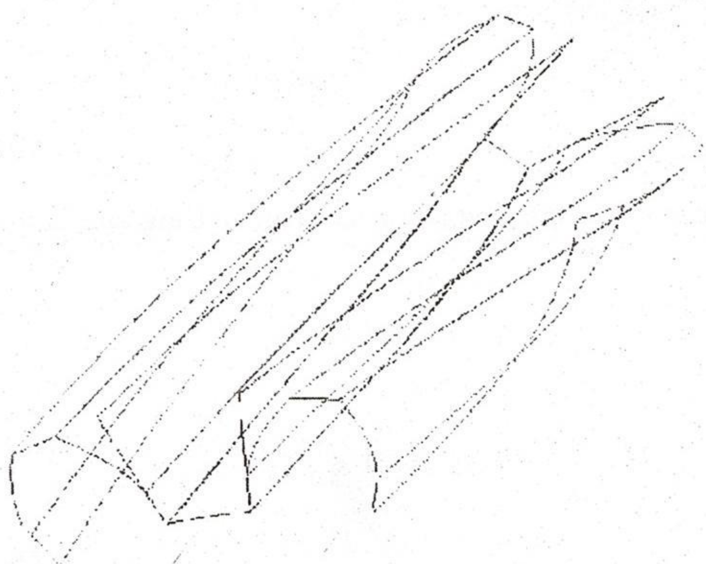

Fig. 3.6a The surface model for making tool path of one gear slot in Unigraphics II software

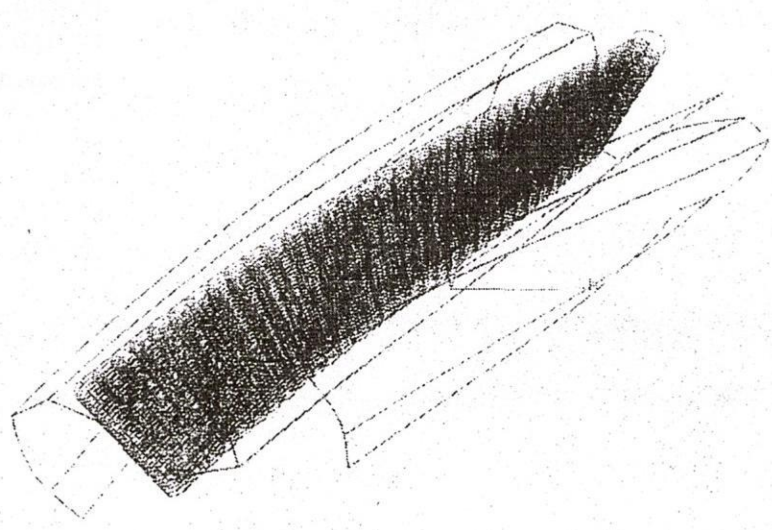

Fig. 3.6b Tool path to machine the first artificial surface in Unigraphics II

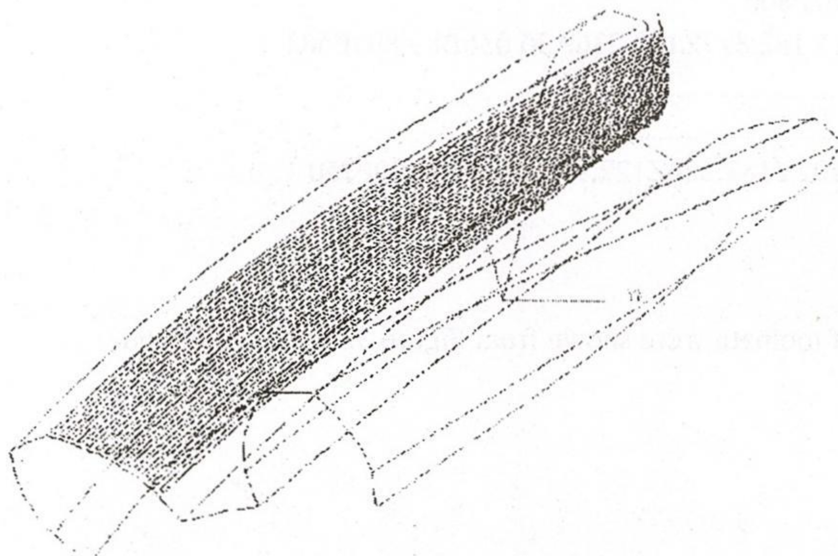

Fig. 3.6c Tool path to machine the first gear Flank in Unigraphics II

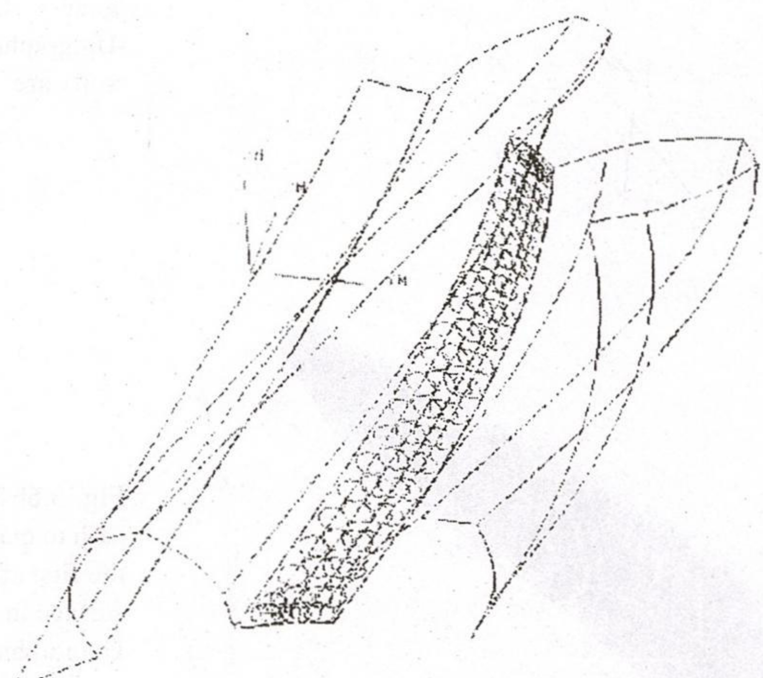

Fig. 3.6d Tool path to machine the dedendum surface in Unigraphics II software

V - CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

• The application of CAM technology and CNC machine in making the spiral bevel gear is a new concept and it has been done successful through this research. In this research, we have established the typical model for linking between CAD/CAM/CAE system together.

• Before spiral bevel gears are made on the specific machine and there are many problems should be encountered as:

- The accuracy of the slide table and rotary axis are not higher than CNC machine

- It is only suitable for job shop production, because with a special parameter of spiral bevel gear we have to manufacture a special tool head corresponding to this kind. While in CNC one tool can be used to machine for many kinds of spiral bevel gear modules

- The combination of enveloped motions to make the gear tooth surface in specific machine is very complicated. While these envelop motions is done by tool only, this is the most significance of CNC machine in making spiral bevel gear. However, specific machine was still used suitable for making the spiral bevel gears in the large production because of high productivity.

•The use of CAM system in Unigraphics II allowed us to select the optimal solution for process planning spiral bevel gear. We can control the required accuracy and observe the machining process. Especially, with the use of "SWARF" milling technique in five axis milling mode which has a lot of advantages such as Reducing in number of clamping set up on machine; Avoiding of undercut phenomena for complicated shape workpiece; Better cutting condition by selecting suitable cutting angle, feed rate, spindle, etc. of tool and because of this will less wear tool; Tool can reach the difficult positions.

• Post Processor Maho600e is very friendly and useful when making the CNC file from the CLS file. However it has some disadvantages should be encountered:

- No have available the menu for indexing workpiece so we have to build a loop (or sub-program) which is derived from the basic DNC program.

- The orientation of the machine coordinate system in CLS file must be corresponding to the machine coordinate system in Post processor Maho600e, so we will meet difficult to select correctly the direction of this MCS on WCS.

- Not flexible for converting coordinate systems between WCS and MCS. The calculation of ORIGIN in Post Processor Maho600e is very complicated, because it is required to determine exactly some coordinates of the machine reference point in the machine coordinate system.

5.2 Recommendations and Future Study

During the research, there are a lot of problems have been arisen in the application of CAD/CAM/CAE/CNC techniques in manufacturing spiral bevel gears such as:

1. The standard for post-processing should be developed

2. The automation of converting coordinate system and indexing in MAHO600e Postprocessor should be supported

3. The selection of correctly incline angle and linear tolerance of tool. Especially, we should use the bull-nose tool the step to cut the artificial surfaces in order to create blending corner and reduce the concentrated stress at the gear root of gear slot.

4. It is preferable to suggest that the spiral bevel gear should be machining only one set up for both turning and milling operation on CNN machine. Because with one set up it is the best way that we can determine precisely the workpiece origin coordinate in the machine coordinate system at the postprocessing step . Therefore, we can reduce so much errors for the next steps following.

5. We should have the integration between CAD system and CNC - CMM for diagnosing the error.

In order to deal with these problems, we should apply the new technique such as high speed milling, optimization the tool angle, optimization the cutting parameters by expert system, use the potential CMM which can scan the profile contour, etc.

Otherwise, by using of the EDM technique, the bigger dimensional spiral bevel wheels will be made by the smaller spiral bevel pinion electrode which can be created exactly on CNC machine This approach is very advanced because we can save so much of processing time and can avoid the undercut problem also the collision when machining the complicated parts.

ỨNG DỤNG MÁY TÍNH TRONG CHẾ TẠO BÁNH RĂNG CÔN XOẮN

Bùi Trí Sĩ – Bohez – Bành Tiến Long

TÓM TẮT : Bánh răng côn xoắn có phẩm chất tốt nhất khi so sánh với các loại bánh răng khác. Tuy nhiên, cho đến nay bánh răng côn xoắn vẩn còn được chế tạo bởi máy chuyên dùng mà sự phối hợp của các chuyển động bao hình để tạo nên bề mặt bánh răng côn xoắn thường rất phức tạp. Vì vậy chất lượng bề mặt của bánh răng thường không chính xác, không ổn định và giá thành cao.

Đề án nghiên cứu này nhằm mục đích áp dụng công nghệ CAM vào trong lĩnh vực cắt kim loại. Đặc biệt, khuynh hướng dùng máy điều khiển chương trình số CNC để gia công bánh răng côn xoắn là giải pháp tốt nhất để có thể bảo đảm những yêu cầu kỹ thuật của bánh răng côn xoắn. Mặt khác, ý nghĩa lớn nhất là nâng cao chất lượng bánh răng côn xoắn và đơn giản hóa rất lớn kết cấu máy công cụ dùng cho chế tạo bánh răng côn xoắn.

Để có thể gia công bánh răng côn xoắn trên máy CNC, một máy CNC với phối hợp điều khiển chuyển động 5 trục cần phải có. Cần thiết có một hệ thống CAD/CAM có khả năng tạo ra qui đạo chuyển động 5 trục và bộ vi xử lý tiêu chuẩn hóa đủ mạnh.

Ý nghĩa lớn nhất của việc sử dụng công nghệ CAM và máy CNC gia công bánh răng côn xoắn là chúng ta có thể sử dụng những file xuất ra từ bộ vi xử ly của máy CNC dùng cho kiểm tra, hiệu chỉnh sai số, mô phỏng và đo đạc chất lượng bề mặt của một đôi bánh răng ăn khớp với nhau.

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